NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

HOLOGRAPHIC INVESTIGATION OF METALLIZED SOLID PROPELLANT COMBUSTION IN TWO-DIMENSIONAL AND THREE-DIMENSIONAL ROCKET MOTORS

by

J.D. Walker

September 1987

Thesis Advisor: D.W. Netzer

Approved for public release; distribution is unlimited

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Naval Postgraduate School; 6b OFFICE SYMBOL (If applicable): Code 67	7a NAME OF MONITORING ORGANIZATION: Naval Postgraduate School
6c ADDRESS (City, State, and ZIP Code): Monterey, California 93943-5000	7b ADDRESS (City, State, and ZIP Code): Monterey, California 93943-5000
8a NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Astronautics Laboratory; 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code): Edwards Air Force Base, California 93523	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO; PROJECT NO F04611-87-X-0040; TASK NO; WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification)
HOLOGRAPHIC INVESTIGATION OF METALLIZED SOLID PROPELLANT COMBUSTION IN TWO-DIMENSIONAL AND THREE-DIMENSIONAL ROCKET MOTORS

12 PERSONAL AUTHOR(S)
Walker, J.D.

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Master's Thesis	FROM ____ TO ____	1987, September	46

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Holography; Metallized Solid Propellant Combustion; Two-Dimensional Rocket Motor; Three-Dimensional Rocket Motor

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This experimental investigation included the design and construction of a new, two-dimensional, rocket motor that could be used to obtain better holographic data than obtained in previous investigations using a small three-dimensional motor. The solid propellant used during this investigation was AP, HTPB, with 2%, 40 micron aluminum particles and 0.25% iron oxide.

Good quality holograms were obtained using the three-dimensional motor at operating pressures of 93 and 94 psia. Successful holographic recordings were also acquired using the new, two-dimensional motor at pressures of 45 and 183 psia.

System limitations and suggested improvements to the apparatus are discussed.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL: Prof. David W. Netzer	22b TELEPHONE (Include Area Code): (408) 646-2980; 22c OFFICE SYMBOL: Code 67Nt

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Holographic Investigation of Metallized Solid Propellant Combustion in Two-Dimensional and Three-Dimensional Rocket Motors

by

J.D. Walker
Lieutenant, United States Navy
B.S., University of Missouri, 1980

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1987

ABSTRACT

This experimental investigation included the design and construction of a new, two-dimensional, rocket motor that could be used to obtain better holographic data than obtained in previous investigations using a small three-dimensional motor. The solid propellant used during this investigation was AP, HTPB, with 2%, 40 micron aluminum particles and 0.25% iron oxide.

Good quality holograms were obtained using the three-dimensional motor at operating pressures of 93 and 94 psia. Successful holographic recordings were also acquired using the new, two-dimensional motor at pressures of 45 and 183 psia.

System limitations and suggested improvements to the apparatus are discussed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Prof. David W. Netzer for his technical advice, enthusiastic support and patience. I'd also like to thank Harry Conner, Pat Hickey, John Moulton, Don Harvey and Ron Raemaker for their technical assistance throughout this investigation.

I would like to thank my wife, Joy, and my daughters, Julie and Jamie, for their supportive love and understanding.

I wish to dedicate this thesis to my lord and savior, Jesus Christ.

I. INTRODUCTION

Solid propellants have long been used for rocket and missile propulsion due to their reliability, low cost, safety and simplicity. Improvements to the performance of solid propellants has mainly come about through the addition of metals, and in particular, aluminum. The advantages of adding aluminum to the propellant include: (1) increased specific impulse, (2) a source for dampening of high frequency combustion pressure oscillations, (3) it remains non-toxic throughout the entire burning process, and (4) an abundancy of supply and relatively low cost. There are also some problems associated with the addition of aluminum. Some of the aluminum particles leave the burning propellant surface immediately and subsequently are rapidly consumed, converting their chemical energy to thermal energy and subsequently, to kinetic energy and increased thrust. Many other aluminum particles will bond to each other and form surface agglomerates. These agglomerates are formed as the metal temperature increases and the aluminum particles come into close contact [Ref. 1]. At temperatures of approximately 700 K [Ref. 2] the particles begin sticking to each other. At 933 K the aluminum reaches its melting point. The expanding aluminum begins causing cracks in its oxide shell, where it leaks out and begins bonding with the

neighboring particles. At 2300 K the aluminum oxide shell melts and the aluminum particles merge into a large agglomerate. These agglomerates, together with large aluminum oxide particles, can decrease the delivered performance of the motor. The large aluminum agglomerates are more difficult to burn completely and large aluminum oxide particles should be small by the time they reach the nozzle in order to minimize two-phase flow losses. Aluminum oxide is also a major contributor to the erosion of motor parts. The particles (large and small) that exit the exhaust nozzle can make the exhaust plume highly visible. The major disadvantages of using aluminum are the decreased specific impulse efficiency (which is largely due to the two-phase flow losses occurring in the nozzle) and the exhaust plume visibility.

Two-phase flow losses are mostly dependent on the particle size in the nozzle. As long as the shear force of the gases is greater than the surface tension of the particles, then the particles will have a tendency to break up, resulting in higher combustion efficiencies and smaller, more desirable droplets in the nozzle [Ref. 3].

By obtaining accurate data inside the motor from the time the particles begin burning on the propellant surface, through the combustion chamber and entering and exiting the exhaust nozzle, it will become possible to make changes in the composition of metallized propellants to improve the

delivered performance. Analytical models, which attempt to predict the effects of the particles, could also be validated and improved. The accurate prediction of exhaust plume signature also requires knowledge of the effects of propellant properties on the particle size distributions entering and leaving the exhaust nozzle.

At the Naval Postgraduate School, pulsed holography is one of the current methods being used to record and collect this highly desired data for particle sizes throughout the different regions of small rocket motors. To obtain good holograms, it is necessary to develop well-documented procedures and techniques. The laser light is capable of penetrating only a certain amount of smoke, which is largely determined by the size and quantity of aluminum oxide particles and binder products in the gas phase. Agents used to bond the propellant into the motor can also contribute to the opacity of the combustion products. Generally, at least a 10% transmittance is required to obtain a good hologram. Another important criterion for acquiring a good hologram is the intensity ratio between the two laser beams. It has been found that a reference beam to scene beam intensity ratio between 5:1 and 10:1 gives the most desirable results. Maintaining this ratio can prove very difficult when the amount of smoke generated varies greatly between each test. It is for these reasons that smoke is the toughest problem to overcome in obtaining a good hologram with accurate,

retrievable data. The burning particles also have "flame envelopes" around them. This creates regions with large density gradients, with the resulting schlieren effects being recorded on the holographic plate. This masks the particles, preventing the particles from being viewed. In order to help eliminate this effect a diffuse scene beam is used. The one drawback to diffuse illumination is that it produces speckle in the hologram, making it difficult to pick out the smaller particles and determine their size. To help reduce the speckle problem, the reconstructed image is placed onto a rapidly rotating mylar disk located at the focal plane of the viewing microscope objective lens. Even under the best circumstances, it is very difficult for particles less than 10 microns to be seen in the hologram. Another technique being developed in a joint effort with the Electrical and Computer Engineering Departments is computer-based image processing. It is hoped that this will allow smaller particles to be observed while at the same time providing particle size distribution data to be rapidly obtained from the hologram.

The actual hologram is produced by placing a holocamera [Ref. 4] around the small windowed rocket motor. A single pulsed ruby laser [Ref. 5] fires a beam into the holocamera; there the beam is split into a scene beam and a reference beam. The scene beam takes one path through the camera, motor window and onto the holographic plate. The reference

beam takes a different path through the camera and onto the plate. The laser used to reconstruct the hologram was a CW krypton laser.

Other techniques used in the past at the Naval Postgraduate School to determine particle sizes from burning propellants have included high speed motion pictures of propellant strands burned in a nitrogen purged combustion bomb. Currently, forward light scattering techniques are also being used with some success.

The objectives of this investigation were:

(1) to obtain good quality holograms at low pressures using a small three-dimensional windowed rocket motor.

(2) to design and construct a new, small, narrow chambered, two-dimensional windowed rocket motor.

(3) to develop experimental techniques for obtaining good quality holograms at low pressures (less than 350 psia) using the new 2-D motor.

Past investigations by Lee [Ref. 6], Yoon [Ref. 7] and Rubin [Ref. 8], produced important data and established good experimental equipment and techniques for this investigation to build on. Lee did his study using a miniature 2-D motor, looking at the particle sizes coming off the burning propellant. Yoon determined a method for obtaining the proper ratio between the reference beam and scene beam. Rubin developed the computer controlled program to trigger the holocamera during the firing sequence. Both Yoon and Rubin worked with a small 3-D motor.

II. EQUIPMENT

A. LASER

The laser system used for this investigation was a single pulsed, ruby laser, shown in Figure 2.1, constructed by TRW, Inc. [Ref. 5]. More reliable and easier to use, this 1978 laser was an upgraded version of the one originally built in 1970, and was specifically designed for studies of solid propellants. The basic components of the laser system were a Q-switched oscillator, a ruby amplifier, a beam-expanding telescope, a dark field alignment autocollimator with an internal zirconium arc lamp, and a 3-milliwatt helium-neon pointing laser. It produced a beam diameter of 3.2 cm at 694.3 nm. Either a 1 joule, 50 nsec pulse or a .25 joule, 10 nsec pulse can be used. The laser also has its own cooling system and two electronic consoles, shown in Figure 2.2, that house the lasers' lamp capacitor banks, charging and safety logic components, and electronic timing circuits.

B. HOLOCAMERA

The lens-assisted holocamera (Figure 2.3) was designed by TRW, Inc. to be illuminated by the ruby laser system described above. The three main components of the holocamera include: (1) the main mirror-beam splitter box, (2) a removable lens-plate box, and (3) a shutter

electronics box. A diffuse filter can also be attached at the exit lens for the scene beam in order to minimize or eliminate schlieren effects while the propellant is burning.

The illuminating beam enters the main mirror-beam splitter box where it is split into the scene beam and reference beam by a series of beam splitters and mirrors. Some lens-assisted holographic techniques have been employed in this holocamera in order to obtain better resolution. In order to obtain the proper ratio between the scene beam and the reference beam intensities, a neutral density filter has been placed inside the shutter box, in the path of the reference beam.

Figure 2.4 shows the removable lens-plate shutter box, where the image is recorded on a 4 x 5 inch glass plate manufactured by AGFA-GEVAERT. The glass plate is attached to a removable brass plate holder which is secured to the lens-plate box by a magnet. This same removable lens-plate box is later used during reconstruction of the hologram. To protect the plate from fogging during the combustion burn, the box also houses a removable electromagnetic, solenoid-driven Uniblitz shutter and a narrow-pass laser line filter.

The shutter electronics box works in conjunction with the shutter and a HP-9836S computer system shown in Figure 2.5. A pressure transducer was connected between the motor and the computer. The desired pressure and time delay to take the hologram was then entered into the computer prior

to firing the motor. When the desired pressure and time delay were reached after ignition, the computer actuated the shutter trigger electronics, which in turn opened the shutter and fired the laser.

C. TWO-DIMENSIONAL MOTOR

In an effort to reduce the distance the laser beam travels through the smoke filled motor, it was decided that a new two-dimensional, small rocket motor with windows, needed to be designed and constructed. Figure 2.6 shows the completed 2-D motor. Designs were made for motors which would operate at pressures of 100, 300 and 500 psia. Due to the shortage of time, only the 100 psia motor was built and operated during this investigation. In order to compare the data obtained from the holograms (and light scattering measurements) using the new two-dimensional motor with that previously acquired with the three-dimensional motor, the nozzle section was designed to have the same rate of change of area.

To operate the motor at 100 psia the solid metallized propellant was cut into two slabs, each one .25 x 2.9 x .75 inches. The required ratio of the propellant burning surface area to the nozzle throat area was determined to be 42.98 for a typical propellant, using the formula:

$$P_c = \left(\frac{A_b a \rho_p C^*}{A_{th} g_c}\right)^{\left[\frac{1}{(1-n)}\right]}$$

Each slab had a constant width of .25 inches throughout the motor and a length of 2.9 inches. This yields $A_{th} = 0.0336$ in^2.

One concern in the design of the new motor was to insure that excessively high flow velocity would not occur within the port of the propellant grain. Numerous calculations were performed utilizing the energy, continuity and momentum equations. In the worst case, a Mach number of 0.31 would be reached at the exit of the propellant section. More details on the numbers, constants and equations used for the two-dimensional motor design can be found in the investigation performed by Pruitt [Ref. 9]. Figure 2.7 shows the vertically mounted, two-dimensional rocket motor and holocamera.

D. THREE-DIMENSIONAL MOTOR

Prior to the completion of the new two-dimensional motor, additional holograms were obtained using the same three-dimensional motor that Rubin [Ref. 8] operated. This allowed time to better examine the procedures and techniques for aligning and operating the motor, as well as developing the holograms.

The short, windowed, three-dimensional motor, shown in Figure 2.8, was constructed of stainless steel, cylindrical in shape, and fired vertically through a graphite exhaust nozzle. Nitrogen purge was passed through an annular filter to keep the 25.0 mm diameter, fused silica windows clean

during operation. The motor also had a pressure sensing line and a burst disk designed to relieve motor pressure, should it ever exceed 1,000 psia.

The propellant used in the motor contained AP, HTPB, 2%, 40 micron aluminum and 0.25% iron oxide. A $BKNO_3$ igniter was used to ignite the propellant. Figure 2.9 shows the components of the three-dimensional rocket motor.

E. HOLOGRAM RECONSTRUCTION

After the hologram has been recorded on a holographic glass plate and developed, it can be reconstructed using the reverse reference beam technique.

The holographic plate is secured to the hologram holder, which in turn is positioned inside the removable lens-plate box. The box is then mounted on a stand positioned near the focal point of a conventional, variable power, trinocular microscope.

A krypton-ion CW gas laser was used to reconstruct the hologram. The laser was positioned at a 60 degree angle from the hologram. The 0.5 watt laser rear illuminated the hologram, creating a real image of the recorded scene on the rotating disk.

A rotating mylar disk was placed at the focal plane of the microscope's objective lens in order to reduce the speckle introduced by the diffuse scene beam. Figure 2.10 shows the apparatus used to reconstruct the holograms.

Figure 2.1 Pulsed Ruby Laser

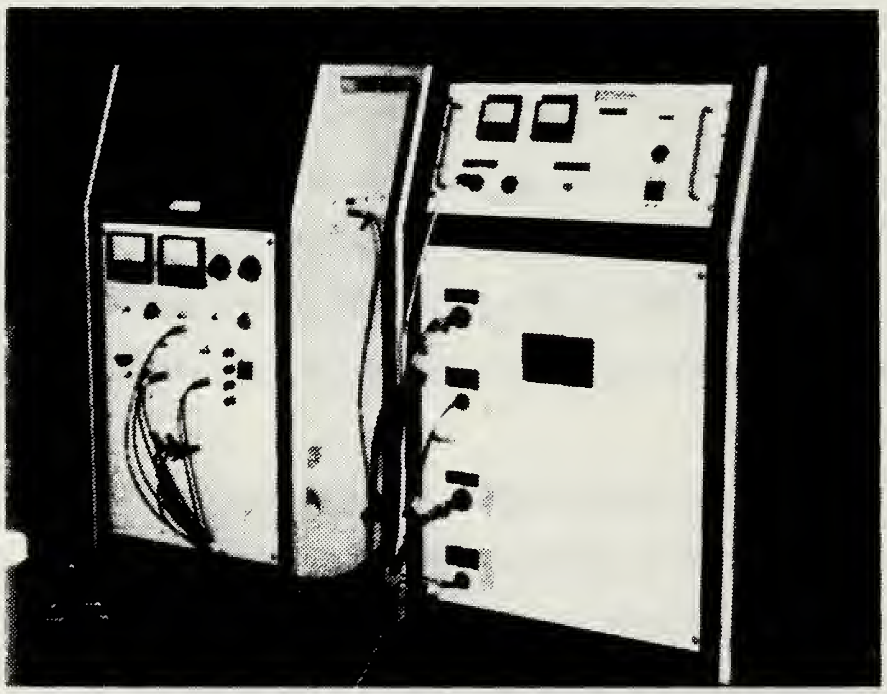


Figure 2.2 Pulsed Ruby Laser Electronic Consoles

Figure 2.3 Holocamera

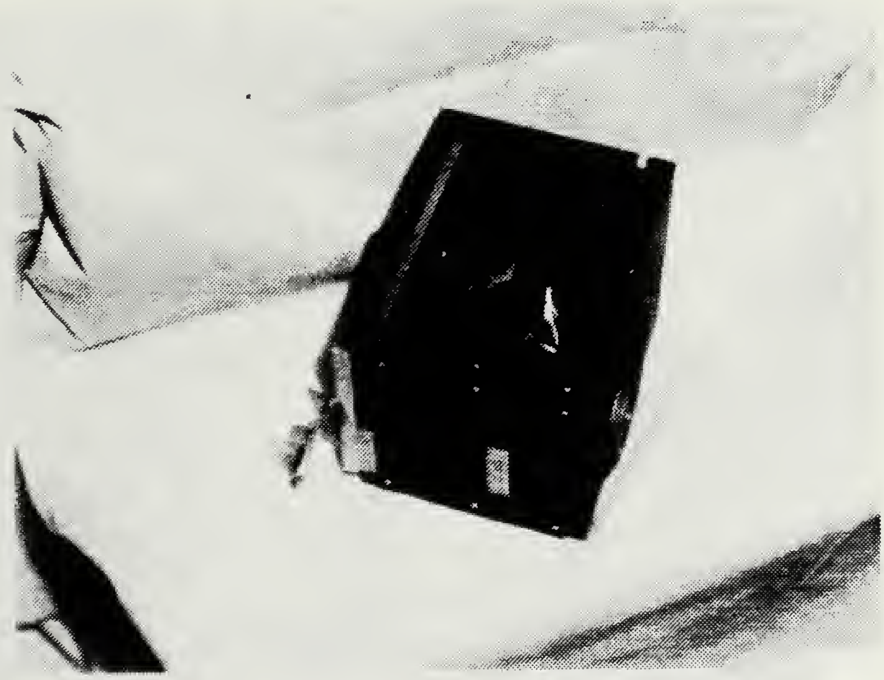


Figure 2.4 Removable Lens-Plate Box

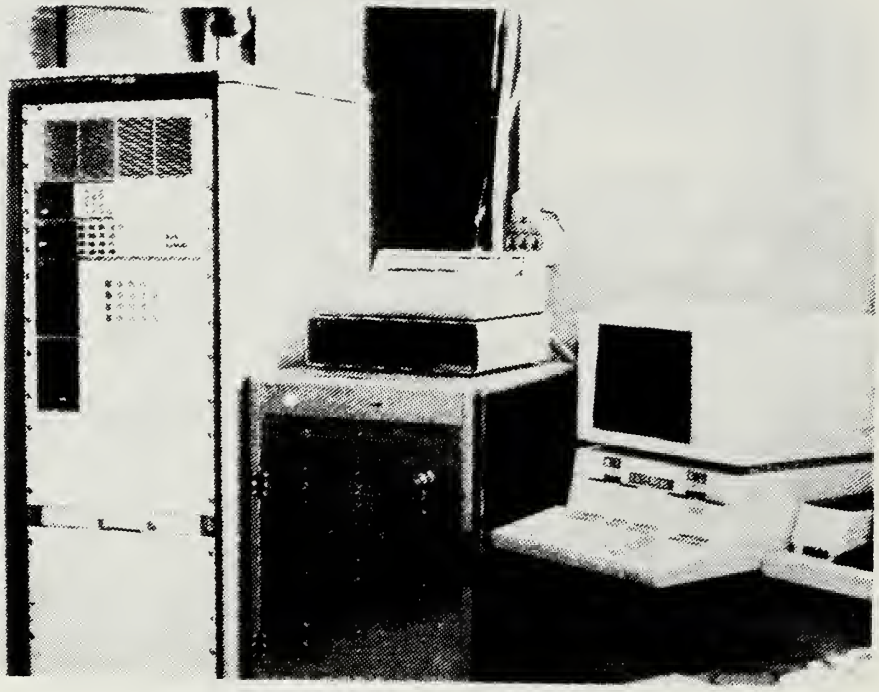


FIgure 2.5 HP-9836S Computer System

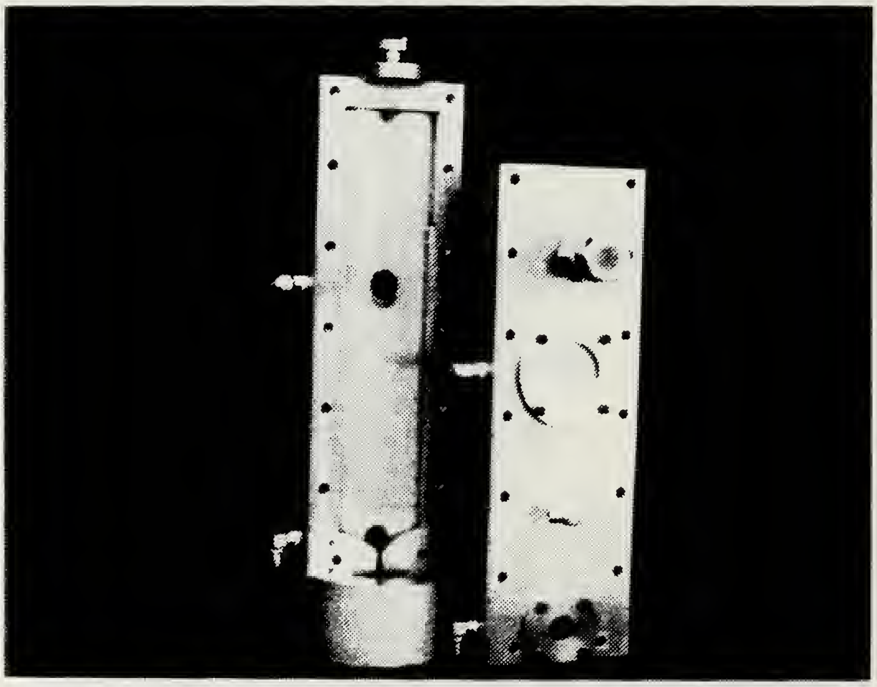


Figure 2.6 Two-Dimensional Rocket Motor

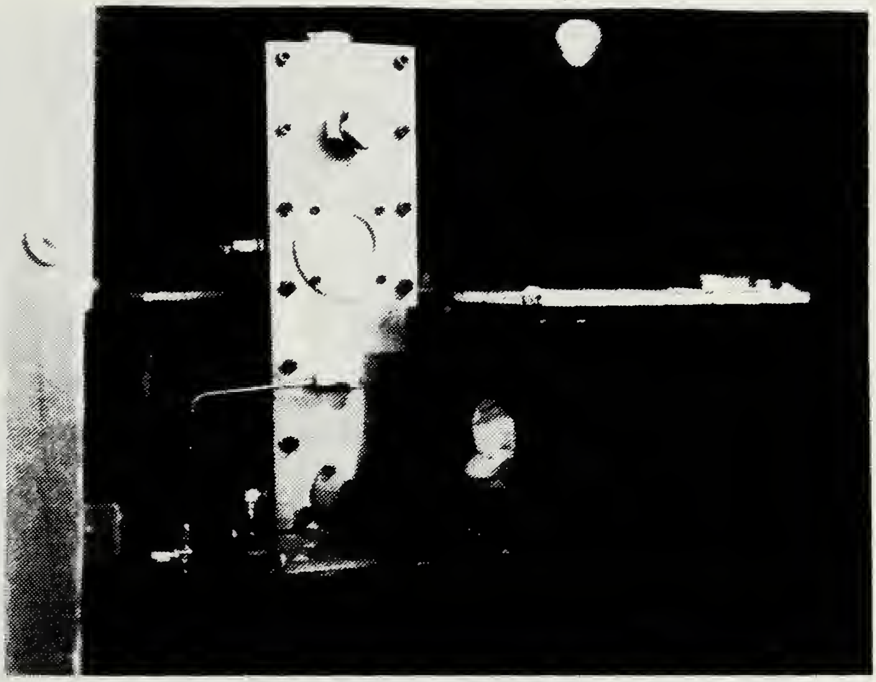


Figure 2.7 Holocamera and Vertically Mounted 2-D Motor

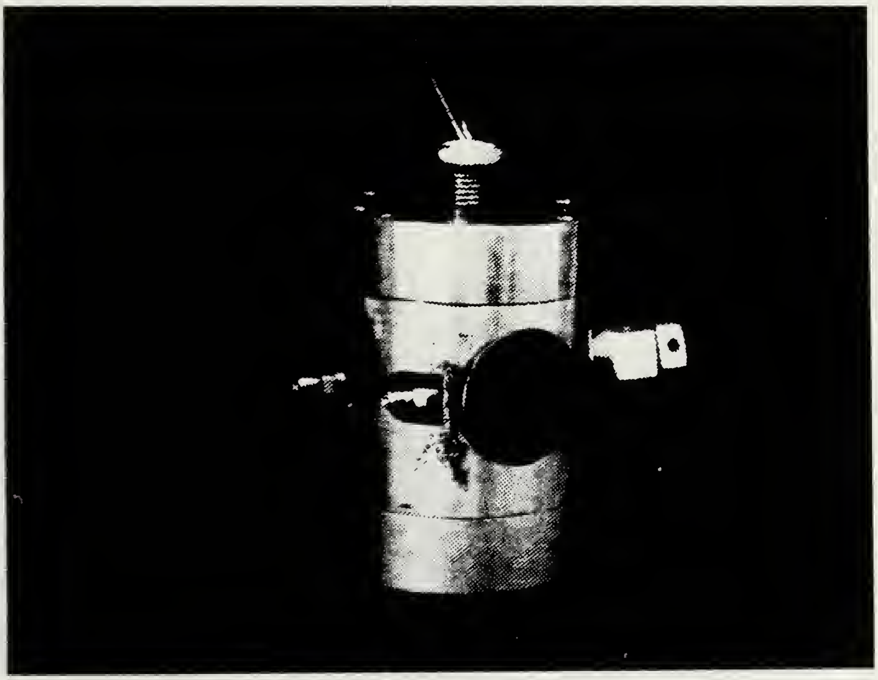


Figure 2.8 Three-Dimensional Motor

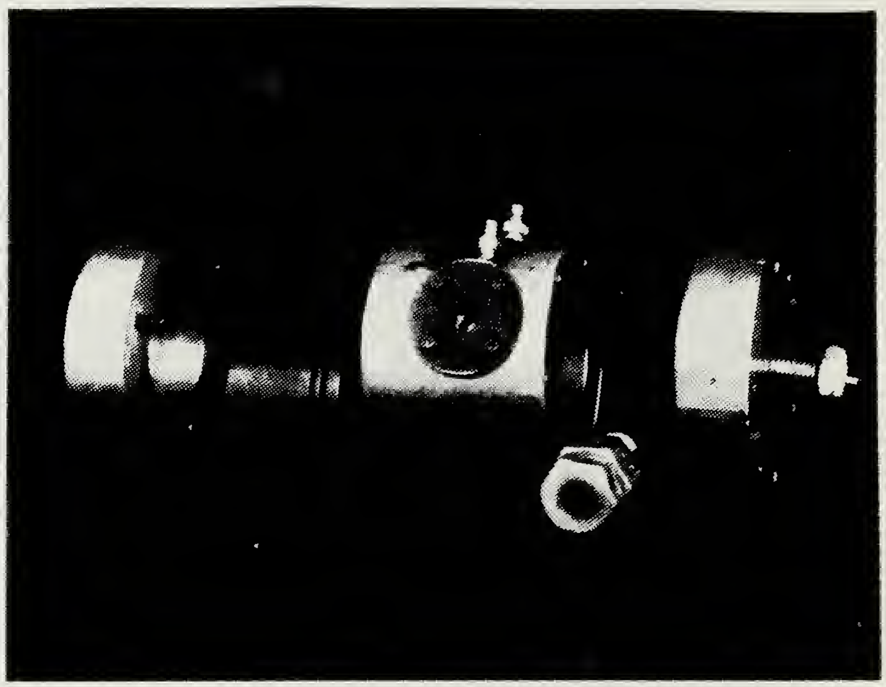


Figure 2.9 Three-Dimensional Rocket Motor Components

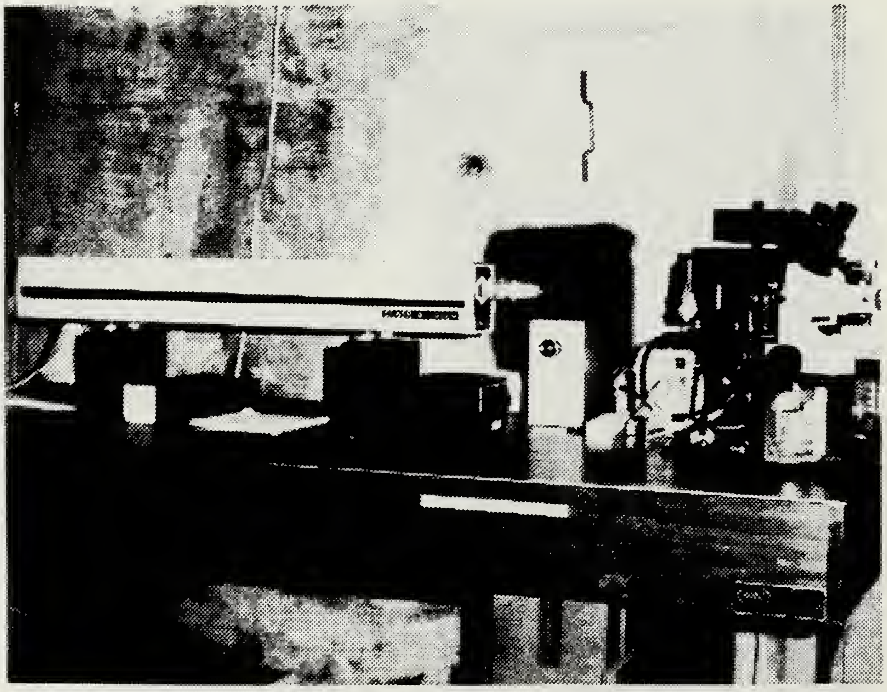


Figure 2.10 Holographic Reconstruction Apparatus

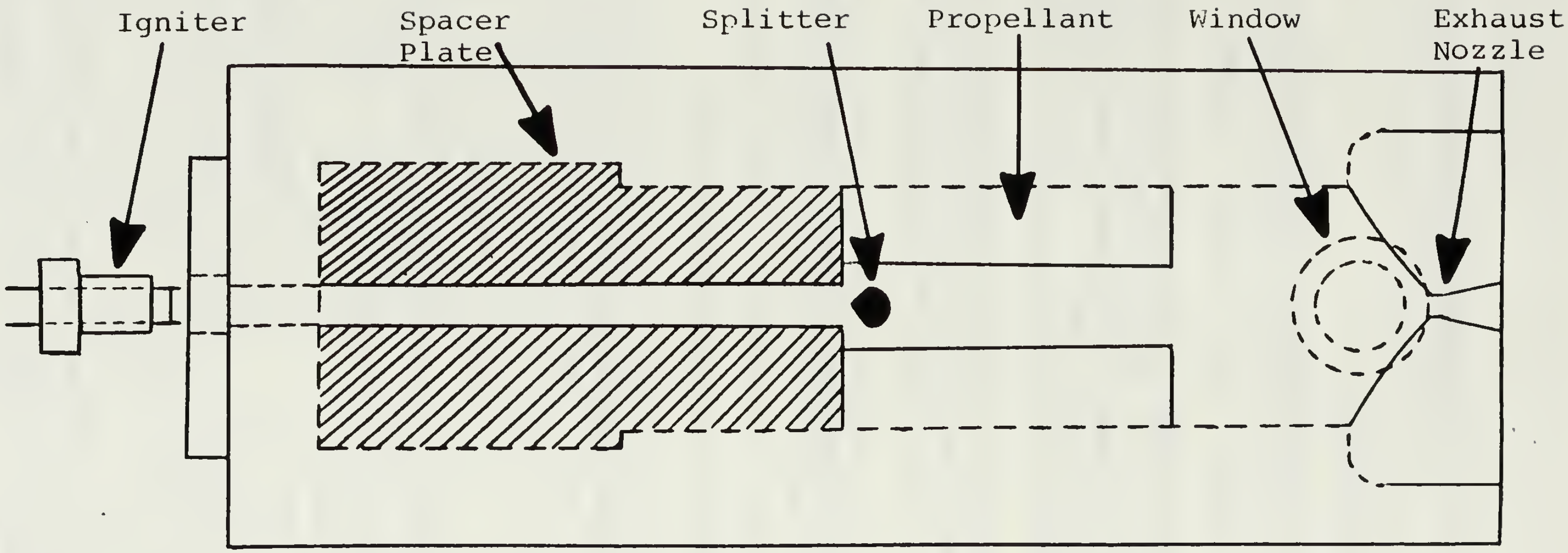


Figure 2.11 Schematic of Two-Dimensional Motor

III. EXPERIMENTAL PROCEDURES

A. SYSTEM CALIBRATION

In order to determine the resolution limits of the holographic system, the single pulsed ruby laser and holocamera were used to produce a hologram of a 1951 USAF resolution bar target. The best resolution limit obtained was approximately 12 microns using a diffuse scene beam. Limits as low as 8.77 microns obtained by Lee [Ref. 6] have been recorded in previous investigations.

B. PRE-FIRING PREPARATION FOR THE TWO-DIMENSIONAL MOTOR

The following is a list of the required steps prior to firing the two-dimensional rocket motor.

1. Bond the propellant inside the rocket motor 24 hours prior to firing using General Electric Hi-Temp gasket material (red RTV). Lightly sand off the remaining uninhibited surface area of the propellant.

2. Construct an igniter (Figure 3.1) by inserting two insulated copper wires through the igniter bolt. After scraping off the thin insulation on the ends of the two wires, solder a 0.015 inch diameter (approximately 0.125 inches long) nichrome wire between them at the end to be inserted into the igniter section. Seal the wire entry holes with epoxy. Fill the igniter section half-way with $BKNO_3$ powder and install the igniter bolt, insuring that the wire is touching the powder and that no wire is shorted to the motor. Check for continuity.

3. Install the one-inch windows, along with their associated filters and pressed fittings, then secure the two-inch steel cover plates. Insure that the windows are clear of any scratches or foreign particles.

4. Install the pressure relief bolt equipped with a 1,000 psia burst disk.

5. Clean and inspect the holocamera optics.

6. Mount the rocket motor vertically to the exhaust system.

7. Connect the nitrogen purge and pressure transducer lines to the rocket motor. Adjust the nitrogen purge as required.

8. Align the holocamera using the He-Ne laser. The scene beam and reference beam are passed through the holocamera and rocket motor onto a calibration holographic plate. When the alignment is complete, secure the rocket motor to the test stand exhaust.

9. Install a holographic plate in the lens-plate holder, then mount the holder on the holocamera and connect to the shutter electronics box.

10. Load the program into the HP-9836S computer system, calibrate the pressure transducer, and ensure that all other instrumentation is turned on and ready to record.

11. Turn the laser system on and allow to warm up at 4.5 kV.

12. Check the igniter for continuity and that there are no grounds to the rocket motor.

13. Connect the igniter and ensure that the battery charger is turned on.

The pre-firing preparation for the three-dimensional motor can be found in the investigation by Rubin [Ref. 8].

C. MOTOR FIRING SEQUENCE

Inside the control room, a Honeywell 1508 Visicorder (Figure 3.2), was used to accurately record the sequence of events that occurred during each motor firing. The printout contained a pressure-time trace and a single pulse along the

ruby laser photodiode trace to mark the precise pressure and instant of time during the motor firing that the laser fired. Figure 3.3 shows the pulsed ruby laser control panel, where the motor firing was manually initiated. The laser was fired automatically after the desired threshold pressure and time delay, that were input to the HP computer, were attained. Following the pre-firing preparation, the sequence of events for firing the motor were as follows.

1. Check all electrical connections.
2. Check all control panel switches for proper positioning.
3. Remove plate from the exhaust pipe.
4. Check that nitrogen purge is properly set.
5. Check to ensure that laser mirrors are all in, and the He-Ne is off.
6. Check that the shutter is plugged in and turned on.
7. Check that the diffuser, filters, and/or target are in place, as desired.
8. Open the reference beam shutter.
9. Slowly raise laser capacitor bank voltage to 20.5 kV.
10. Insure that the computer program is in the "ready to fire" mode.
11. Sound the exterior warning horn two times.
12. Turn on the rocket motor warning lights and alarm.
13. Turn on nitrogen purge.
14. Charge the capacitor bank.
15. Start the Visicorder.
16. Proceed with firing the rocket motor at the laser control panel.

17. After the motor has fired, discharge the capacitor bank and turn off the nitrogen purge and Visicorder.

18. Turn off the warning lights and alarms.

19. Secure the laser system and all test cell equipment.

D. HOLOGRAM PROCESSING

Upon completion of firing the rocket motor, the removable lens-plate box, with the exposed holographic plate inside, was removed from the holocamera and taken into a darkroom where the hologram was developed as follows.

1. The plate was dipped in Kodak HRP developer in 10 second intervals until an image was clearly visible using a Kodak safelight.

2. The plate was placed in Kodak Stop Bath for 30 seconds, then rinsed in fresh water.

3. The plate was placed in Kodak Hypo Fix bath for 5 minutes to set the image onto the plate.

4. The plate was set in fresh running water for 10 minutes.

5. The plate was immersed in Kodak Photo-Flo for 30 seconds and slowly removed.

6. The plate was allowed to air dry for approximately 3 hours.

E. HOLOGRAM RECONSTRUCTION

The hologram was reconstructed with the aid of a krypton-ion CW gas laser and a trinocular microscope, using the reverse reference beam technique as follows.

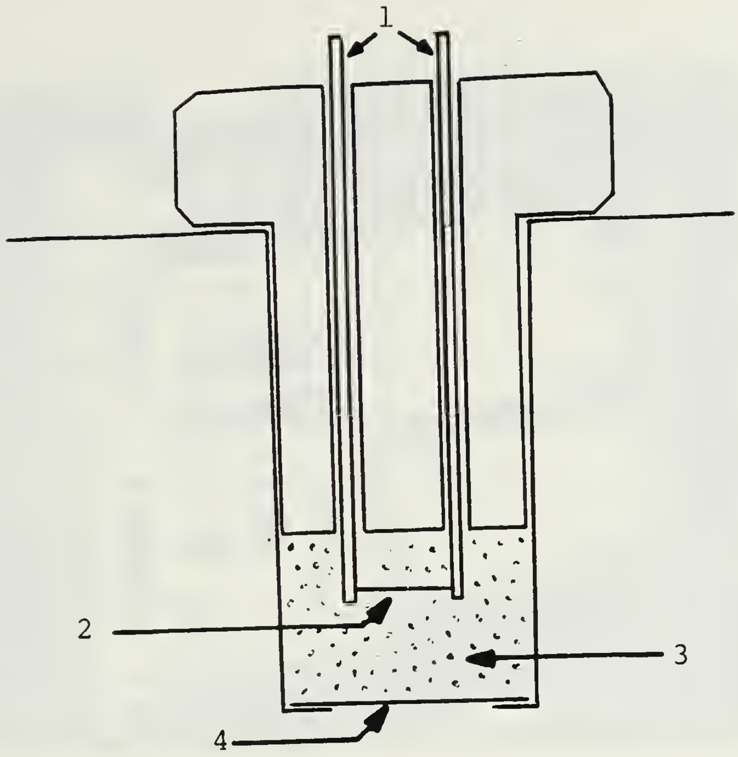
1. Initiate cooling water for the laser and turn the system on in accordance with the instruction manual.

2. Mount the lens-plate holder, with the hologram inside, onto the microscope viewing stand at a 60 degree angle with the laser.

3. With the mylar disk motionless, adjust the microscope for proper viewing at the focal point.

4. Fully open the laser aperture and shutter; remove the shutters on the lens-plate box; and rotate the mylar disk.

5. Adjust the microscope as necessary to view the hologram.



1. Copper Wires
2. Nichrome Wire
3. $BKNO_3$ Powder
4. Paper Wad

Figure 3.1 $BKNO_3$ Igniter

Figure 3.2 Honeywell 1508 Visicorder

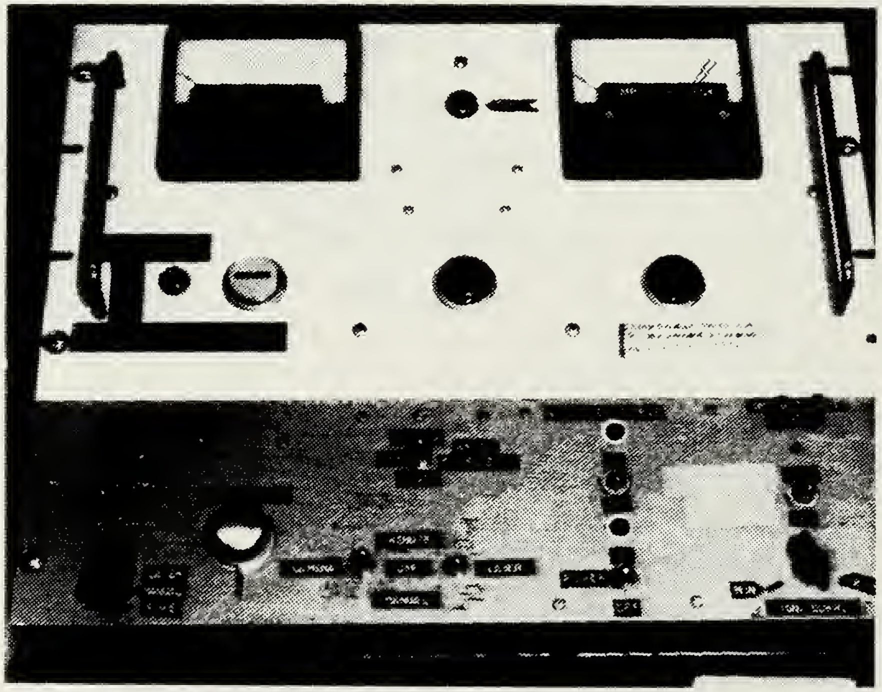


Figure 3.3 Pulsed Ruby Laser Control Panel

IV. RESULTS AND DISCUSSION

A. THREE-DIMENSIONAL ROCKET MOTOR

One of the objectives of this investigation was to obtain good quality holograms at low pressures (approximately 100 psia) using a small, three-dimensional, windowed rocket motor. A summary of the 10 rocket motor firings attempted can be found in Table I.

Since the biggest problem in obtaining a good hologram was smoke, and the ability of the scene beam to penetrate the smoke in the combustion chamber, different techniques were tried in order to more consistently acquire good quality holograms.

A 0.03 diameter wire was attached to the outside of the motor rear window, directly in the line of fire of the laser scene beam. During reconstruction of the hologram, if this wire could be found and clearly focused, then it could quickly be determined that the hologram had been developed properly and a sufficient amount of the scene beam had penetrated the windows and smoke-filled motor. Larger particles and agglomerates in the combustion chamber could then be observed, if present.

For consistency during all the motor firings, the only propellant used was AP, HTPB, 2%, 40 micron aluminum with 0.25% iron oxide. Each propellant grain was cut in a

circular donut shape, with a 0.70 inch inner diameter, a 2.95 inch outer diameter, and cut 1.0 inch long. The nozzle throat diameter was also held constant at 0.335 inches. Each propellant grain was inhibited along the outer diameter and top with RTV.

Since the RTV inhibitor contributed to the amount of smoke during the firings, better quality holograms were observed when thinner coatings of the RTV were applied during the bonding of the propellant.

The amount of particles and residue that built up on the windows during the firings was largely influenced by the amount of pressure supplied by the window nitrogen purge lines. At nitrogen pressures less than 200 psia, the pressure was too low to keep the dust and particles from completely covering the windows. Using a nitrogen pressure greater than 700 psia seemed to cause such violent circulation flow in the motor that the smoke was sometimes forced into the window chambers rather than away from them. The windows were kept cleanest when the nitrogen purge was operated between 300 and 500 psia.

Event 1 was a test run for the rocket motor and computer. No holographic plate was loaded. The propellant ignited properly, the motor operated with no problems, and the laser fired as programmed.

Event 2 was not as successful. Three attempts were made to ignite the propellant, but the motor failed to fire. It

was determined that some of the stored propellant had been exposed to excessive amounts of water and moisture during a previous investigation, making it difficult to ignite and slow to burn.

During Event 3, the motor fired well and the laser, computer and recording equipment all functioned properly, but no hologram was exposed on the plate. The nitrogen purge was operated at 150 psia, but large amounts of white dust were caked on the windows. There was no reference beam or scene beam developed on the glass plate, and the reference beam shutter was open during the firing. The reason for the hologram not developing was undetermined.

Event 4 again resulted in the propellant not firing. Three attempts were made, each time with the igniter firing properly, but the propellant failed to ignite. Three possibilities were examined. First, this could have been more of the bad propellant that had been over-exposed to water. Second, the propellant had been bonded into the motor five days prior to firing, and even though it had been properly stored during those five days, perhaps that delay contributed to the problem of igniting the propellant. It was then determined that in subsequent attempts the motor would be fired within 24 hours of the propellant being bonded. Third, a splitter bar was installed at the end of the igniter so the $BKNO_3$ powder would be fired directly onto the surface of the propellant.

Event 5 resulted in the first good hologram, though a collimated light was used and the scene beam was brighter than desired on the hologram. The windows stayed clean using a nitrogen purge pressure of 300 psia. It was decided that in the remainder of the firings the diffuse filter would be used to obtain a better quality hologram.

Event 6 failed to produce a hologram after two attempts. The first igniter fired properly, but the propellant didn't ignite and the capacitor banks discharged on their own. Another attempt was made with the same results. After an investigation of the equipment and instrumentation, an open circuit was found in the green wire on the shutter. The wire was properly soldered, and the shutter was then tested and found to work correctly. Another igniter was connected and a third attempt was made at firing the motor. The igniter and motor fired properly, but the laser failed to fire until after the propellant had burned out and there was zero pressure inside the motor. It was suspected that the probable cause was a build-up of dust and particles on the shutter while it was being worked on, causing it to react slowly. All the equipment and instrumentation was cleaned and checked for proper connections, then checked and found to operate properly using the dead weight tester.

Event 7 was a test firing of the rocket motor following the work that was completed on the test equipment. A hologram was taken of the resolution target.

After Event 7, in order to accommodate a new investigation at the laboratory, the solid propellant rocket motor test cell required some new construction and rearranging of the test equipment. The next 11 days were spent moving and realigning the investigation apparatus in preparation for firing again.

Problems again with the propellant igniting during Event 8 prevented the motor from firing.

For Event 9 the exposed part of the propellant, after it was bonded in the motor, was lightly sanded so a thin layer of loose propellant particles would exist on the outer surface exposed to the igniter flame. This appeared to work well as the motor fired with the first igniter, the windows stayed fairly clean using a nitrogen purge pressure of 450 psia, and the result was a good hologram.

During Event 10 the same circumstances occurred as happened in Event 6. Again, the problem was found to be an open circuit in the shutter wiring. After repair, the motor was fired again, resulting in a good hologram. The nitrogen purge pressure was maintained at 400 psia and the windows appeared cleaner than in Event 9, where the purge was 50 psia higher.

B. TWO-DIMENSIONAL ROCKET MOTOR

The new two-dimensional motor was completed on August 3, 1987, and was test fired three times during the next 10 days, prior to attempting to obtain a hologram. Minor

design changes were made in the motor and igniter. A splitter bar was added to the propellant chamber to get a more direct ignition flame striking the propellant surface. On that same surface area of the propellant, a thin layer of black powder/glue was added to enhance ignition. The window chamber in the new two-dimensional motor was nearly one inch longer than in the three-dimensional motor. The purge filter was also more porous and 0.06 inch thicker. In order to get enough nitrogen through the filters to keep the windows clean and prevent the window chambers from filling up with smoke and particles, the nitrogen pressure needed to be nearly doubled. The optimum pressure was found to be from 800 to 900 psia for the nitrogen purge. The same type propellant was used as with the three-dimensional motor. All sides of the propellant were inhibited with RTV except the 0.25 x 2.9 inch side along the igniter path. Special attention had to be given when cutting the propellant in order to obtain the design pressure. The propellant burning surface area was varied in several of the firings in order to see how closely the predicted combustion chamber pressures would come to those for which the motor was designed, given a fixed throat area. The more accurately the propellant was cut, the closer the predicted pressure came to the design specification. This added validity to the design and proper construction of the motor.

Event 11 (Table II) produced a good hologram, but also raised some questions. When the equipment was being changed around in the test cell, one of the needle valves in the nitrogen purge lines for the windows was replaced with a ball valve. The window that utilized this new valve was not as clean as the other one. Therefore, it was decided that the nitrogen pressure would be increased from 750 to 850 psia to compensate for the different type valve. The maximum pressure in the motor only reached 45 psia when it was expected to be closer to 100 psia. It was noted prior to the firing that the propellant had been cut unevenly and thinner than specified, and as such, was thought to be the cause of the lower pressure.

For Event 12, the burning surface area of the propellant was doubled from 2.9 to 5.8 inches long. The motor reached a maximum pressure of 425 psia when the burst disk ruptured.

Event 13 resulted in a poor hologram because the one window, with the ball valve in the nitrogen purge line, was too dirty. The ball valve was then replaced with a needle valve. During the repair, one of the lines was found to have too small an orifice. It was drilled out and the nitrogen purge line tested properly.

For Event 14 the propellant slab was cut 3.75 inches long. Calculated pressure was 181 psia; maximum pressure was 183 psia. A nitrogen pressure of 850 psia kept the windows clean and the holograms turned out excellent. The

particle diameters in the hologram were less than 15 microns, and difficult to see.

For Event 15, two spacer bars (see Figure 2.11) were constructed and placed in the propellant chamber in order to move the propellant closer to the window. This was done in an attempt to get a hologram of the aluminum particles soon after leaving the burning propellant slab. Though the nitrogen purge pressure was increased to 900 psia, it was not enough to overcome the combination of the 276 psia maximum pressure reached in the motor and the high velocity of the particles as they went by the window cavity prior to entering the exhaust nozzle. A large build-up of HCl fog and black powder particles on the windows prevented any chance of acquiring a good hologram.

In an effort to reduce the entrance area to the window chamber, for Event 16, washers were constructed to reduce the $\frac{5}{8}$" diameter hole to a $\frac{3}{8}$" diameter hole. The nitrogen purge filters were also sanded down to make room for the washers to fit. No black powder was used to help ignite the propellant, which contributed to the build-up on the windows during Event 15. The motor fired properly, but the Visicorder and computer never received any pressure information during the run, so the laser never fired. The propellant slabs were cut 2.0 inches long, to look at a lower pressure in the motor, and a 500 psia purge was used on the windows. The windows still had a heavy layer of

particles on them after the run. The pressure lines from the transducer to the motor were thoroughly cleaned after the run, and tested for proper operation.

V. CONCLUSIONS AND RECOMMENDATIONS

The new two-dimensional rocket motor proved itself to be well-designed and constructed. It was found capable of producing good quality holograms at pressures up to 183 psia, using a 2% aluminum solid propellant, and preventing a build-up of moisture and particles on the surface areas of the windows during the run. Due to the length of the combustion chamber in the 2-D motor, it was very difficult to find any large particles or agglomerates that had not already burned down to particles and droplets less than 15 microns by the time they reached the exhaust nozzle. The inability of the nitrogen purge to consistently keep the windows clean could be caused by the close proximity of the window port to the nozzle throat, where the particles are approaching Mach one, and/or the large entrance (0.625 inch diameter) between the exhaust nozzle throat and the window cavity. The more precisely the propellant was cut to specifications, the more accurately the motor operated at the designed pressure. Because of the small quantity of propellant used during the burn, small changes in the size of the propellant resulted in large differences in the designed operating pressure. The major problem during this investigation was consistently keeping the windows clean enough to obtain a good quality hologram.

It is recommended that the following suggestions be incorporated for any further investigations.

1. Starting at a motor operating pressure of 100 psia, work on improving the techniques and procedures for consistently keeping the windows clean. Investigate using a thinner, less porous filter for the nitrogen purge, and ways of decreasing the entrance area from the nozzle chamber into the window cavity.

2. Design a new way of mounting the motor so that holograms can be taken through both the 1" and the 2" windows.

3. Since the new two-dimensional motor design was found to be a good one, that was well constructed and operated properly, use the designs that already exist and construct the motors designed to operate at 300 and 500 psia.

4. Investigate the possibility of installing a third window on the new rocket motors, in-between the two windows that already exist, so that the particle sizes can be examined in the propellant chamber, combustion chamber and the exhaust nozzle entrance section.

5. Starting at 100 psia, obtain good quality holograms through each of the windows, and continue that process, at 100 psia intervals, up to 1,000 psia.

TABLE I

SUMMARY OF THREE-DIMENSIONAL ROCKET MOTOR FIRINGS

Event	Threshold Pressure (psia)	Time Delay (sec)	P_c at which Hologram was Recorded (psia)	Maximum Pressure (psia)	Burn Time (sec)	Remarks
1	25	0.5	50	133	3.1	No hologram
2	-	-	-	-	-	Propellant did not ignite
3	25	0.5	54	74	5.3	No hologram
4	-	-	-	-	-	Propellant did not ignite
5	25	0.3	34	94	5.0	Good hologram
6	25	1.0	-	114	3.1	No hologram
7	-	-	-	-	-	Test firing
8	-	-	-	-	-	Propellant did not ignite
9	50	0.2	93	93	4.7	Good hologram
10	50	0.1	93	93	4.8	Good hologram

TABLE II

SUMMARY OF TWO-DIMENSIONAL ROCKET MOTOR FIRINGS

Event	Threshold Pressure (psia)	Time Delay (sec)	P_C at which Hologram was Recorded (psia)	Maximum Pressure (psia)	Burn Time (sec)	Remarks
11	25	0.3	36	45	5.8	Good hologram
12	25	1.5	-	425	1.1	Burst disk ruptured
13	25	1.5	320	323	2.7	Windows too dirty
14	25	1.0	175	183	3.9	Good hologram
15	25	1.1	255	276	3.1	No hologram
16	25	0.5	-	-	-	No hologram

LIST OF REFERENCES

1. Gany, A. and Caveny, L.H., "Agglomeration and Ignition Mechanism of Aluminum Particles in Solid Propellants," Proceedings of 17th International Symposium on Combustion, August 1978.

2. Kraeutle, K.J., "The Behavior of Aluminum During Subignition Heating and its Dependence on Environmental Conditions and Particle Properties," Proceedings of 9th JANNAF Combustion Meeting, Vol. I, CPIA Publication 231, Chemical Information Agency, Silver Spring, Maryland, December 1972, pp. 325-340.

3. Caveny, L.H. and Gany, A., "Breakup of Al/Al_2O_3 Agglomerates in Accelerating Flow Fields," Proceedings of 17th Aerospace Sciences Meeting, No. 79-0300, 1979.

4. Air Force Rocket Propulsion Laboratory, AFRPL-TM-78-12, Operation Manual for the Lens-Assisted Multipurpose Holocamera with Reflected Light Option, by R.F. Wuerker and R.A. Briones, July 1978.

5. Air Force Rocket Propellant Laboratory, AFRPL-TM-78-11, Instruction Manual for the Improved Ruby Laser Holographic Illuminator, by Briones, R.A. and Wuerker, R.F., July 1978.

6. Lee, Y.S., Holographic Investigation of Solid Propellant Combustion in a Two-Dimensional Motor, M.S. Thesis, Naval Postgraduate School, September 1984.

7. Yoon, S.C., Holographic Investigation of Solid Propellant Combustion in a Three-Dimensional Motor, M.S. Thesis, Naval Postgraduate School, December 1985.

8. Rubin, J.B., Holographic Investigation of Metallized Solid Propellant Combustion in a Three-Dimensional Motor, M.S. Thesis, Naval Postgraduate School, September 1986.

9. Pruitt, T.E., Measurement of Particle Size Distribution in a Solid Propellant Rocket Motor Using Light Scattering, M.S. Thesis, Naval Postgraduate School, June 1987.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93943-5002	2
3.	Prof. M.F. Platzer, Code 67Pl Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5004	1
4.	Prof. D.W. Netzer, Code 67 Nt Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5004	2
5.	J.D. Walker 13564 Grain Lane San Diego, California 92129	4
6.	James D. Walker 917 South IRA Court Anaheim, California 92804	2

Thesis
W222127 Walker
c.1 Holographic investigation of metallized solid propellant combustion in two-dimensional and three-dimensional rocket motors.